ADVANCES IN CRYOMODULE DESIGN AND NEW APPROCHES

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Abstract

This paper presents the experience gained designing, constructing and commissioning the TESLA Test Facility (TTF) cryomodules, from the prototype to the most recent version that fulfills the TESLA requirements. The new solutions adopted in terms of radiation shields and cavity fixtures will be particularly discussed due to their impact on cost and performance. Based on this experience some ideas are presented which should be applied to the cryomodule design for the new generation of high current proton linacs.

1 TTF CRYOMODULE

One of the principal goals of the ongoing TESLA Test Facility (TTF) is to study the production of low cost and reliable cryomodules meeting the stringent requirements for the TESLA linear collider [1,2]. Each cryomodule contains 8 superconducting RF cavities cooled to 2 K, a quadrupole magnet package cooled to 4.5 K, thermal shields cooled to 70 K and 4.5 K, active and passive magnetic shielding, cryogenic service pipes and all associated instrumentation. The axes of the 8 cavities must be aligned to the ideal beam axis to within ± 0.5 mm and those of the quadrupoles to within ± 0.1 mm. As proven on TTF, but for the fully predictable parallel displacement, the alignment of the active elements performed at room temperature remains fixed after cool down and during operations. The cryostat must be designed so that there are no resonant vibration modes near the 10 Hz operating frequency of the accelerator. Although dynamic loads associated with the operation of the RF and the beam dominate the heat load, reasonable efforts to reduce the static heat leak into the cryostat are necessary.

The first cryomodule prototype was tested at DESY in early June 1997 [3]. Table 1 compares the measured and expected static heat leak values for the 70 K, 4.5 K and 1.8 K temperature levels.

Table 1. Comparison of Measured and Predicted Static Heat Leaks of the Prototype

Temperature Level	Predicted Static Heat Leak (W)	Measured Static Heat Leak (W)
70 K	76.8	90
4.5 K	13.9	23
1.8 K	2.8	6

Due to the huge number of cables for sensors, including 144 coaxials cables for the 2 K Wire Position Monitors (WPM), and to the two optical windows for cold alignment checks, these values have been considered adequate, taking into account that they include the end and feed caps.

The need for improvements has been dictated by cost considerations, which are dominated by the thermal shields. Special copper braids connected to stainless steel cooling pipes cool these shields. Moreover, fabrication and assembling experience showed that the criteria used to define the general fabrication tolerances were inadequate and expensive [3]. Therefore, a new design was developed by INFN that includes “finger welded” shields and a completely different philosophy for mechanical tolerances and dimensional control during fabrication [4]. This design, supported by an extensive use of FEM computer simulations [5], was discussed and approved by the TESLA Collaboration and two improved cryostats were ordered from the same Italian Company (ZANON), at a price that was less than one half that of the prototype.

The very good results obtained with these second-generation cryostats have been extensively reported elsewhere [6]. In particular, the measured static losses are close to the predicted values, the assembling procedure is much easier, and a more precise and stable alignment of the active elements (cavities and quadrupole package) is possible. As a consequence the prototype cryomodule has been rebuilt to be equivalent to the other two units.

Exploiting the experience gained from the commissioning and operation of the three cryomodules already installed at DESY, a third generation cryostat has been designed by INFN to completely meet the TESLA Collider requirements [7]. An evaluation of each component and its influence on the general layout led to the decision to reduce the vacuum vessel size allowing use of a standard pipeline tube. Checking all possible solutions, a 38-inch (0.98 m) standard pipe (3/8’’thick) was chosen. Three of these new cryostats are now in fabrication at ZANON and their delivery is expected in March 2000.

To arrange all components in the smaller vacuum vessel, the thermal “finger welded” shields were redesigned, optimizing their configuration to the reduced volume and allowing sufficient margin such that interference would not result from tolerance stack with the standard pipe. The major improvement that permitted the

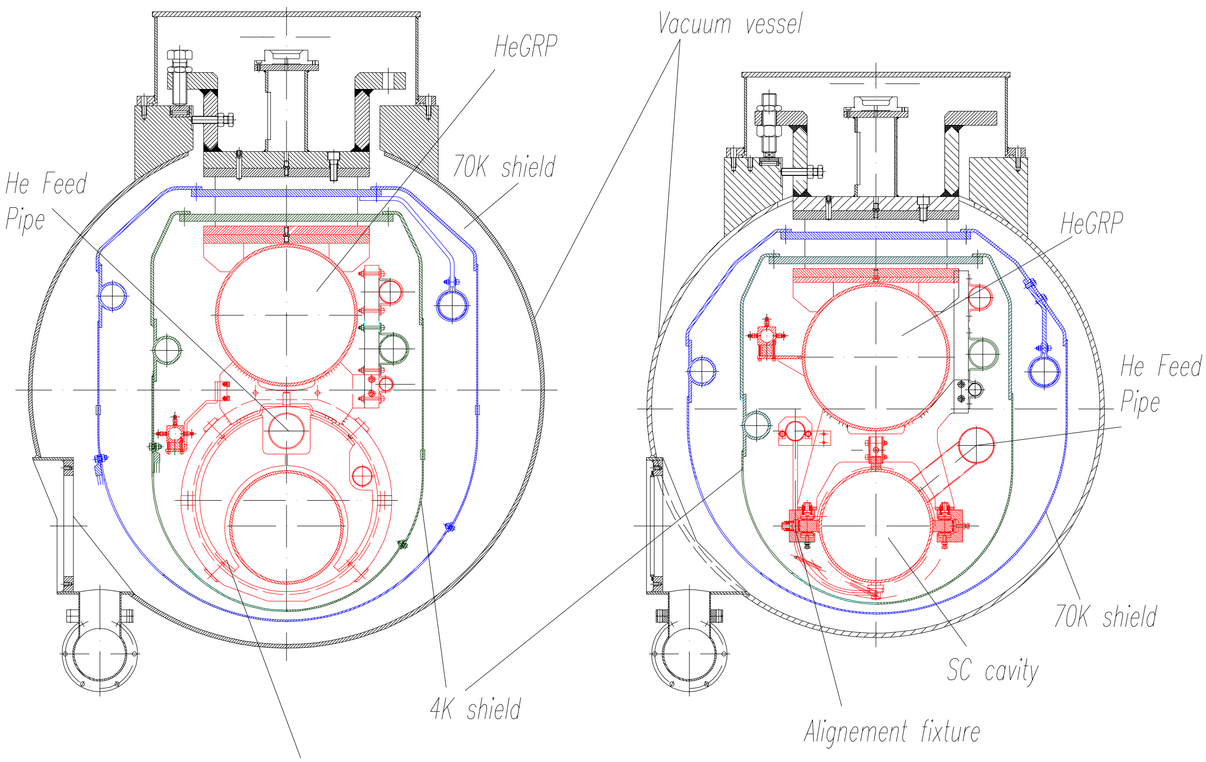

Figure 1. Comparison between second (left) and third (right) generation TESLA cryomodules. The components have been redistributed to fit the smaller vacuum vessel, a 38'' standard pipeline tube.

reduction of the cross section has been the use of an off-axis helium feed pipe. The superfluid helium distribution required it to stay above the helium tank level and below the gas return pipe. In this way, the "off-axis solution" allowed the cavity axis to move closer to the Helium Gas Return Pipe (HeGRP). For a comparison between the second and third generation TESLA cryomodules, the two cross sections are presented together in Fig. 1.

The new cavity support, to be described presently, also requires less volume in the lower region of the cross section with respect to the previous design [4].

2 THERMAL SHIELD

The cryogenic optimization of the TESLA module [3] requires two thermal shields at 4.2 K and at 70 K, respectively. The shields are manufactured from aluminum (1050) and are both made of a roof (divided in two sections, each about 6 meters long) that supports eight panels. The panel length is 1.4 m, except for the first and the last unit. The shield panel length has been chosen in order to adjust for differential contractions between the aluminum shield and stainless steelvacuum vessel, and to allow the coupler holes to follow the cooling cones.

The shield cross-sections have been adapted to the smaller vessel with a rounder shape. The cooling pipe, as in second generation cryomodule, is an aluminum pipe, "finger welded" [4] to the shield roof and to the panels. A bimetallic junction makes the transition to stainless steel in the connection region between cryomodules. The shield geometry has been checked by a finite element code to test for cooldown deformations and thermal inertia.

The results show that a 12-hour linear cooldown produces thermal gradients of about 60 K (Fig. 2) that induce deformations of ~10 mm (Fig. 3), which are compatible with the geometric free space in the section. In order to ease the fabrication and to decrease the cost, the 6-meter shield roofs have been divided in two sections, which are rigidly connected by riveted-welded plates. This heat transfer discontinuity has been included in the model in order to check its influence.

Using the temperature field calculated during the cooldown, a thermo-mechanical analysis has been performed in order to obtain the deformation and stress distributions in the aluminum shields. The results show a lateral bending of the shields, due to the asymmetric cooling ("banana" effect [5]) of about 10 mm, while the maximal stresses are within 30 MPa (the results are shown in Fig. 4). The shield panels and cooling pipes are used to cool other parts of the cryomodule. The post plates, which support the cold mass and the shield roofs, need to be kept at different temperatures. In particular, the lateral post plates are connected to the shields with sliding supports, which do not assure a good heat exchange.

To achieve post cooling, short and very flexible copper braids have been used. The same solution has been used for the coupler cones. The cones have been redesigned (Fig. 1) to ease fabrication and assembly. This solution has been tested during the cooldown of module number two and sensors showed it worked correctly.

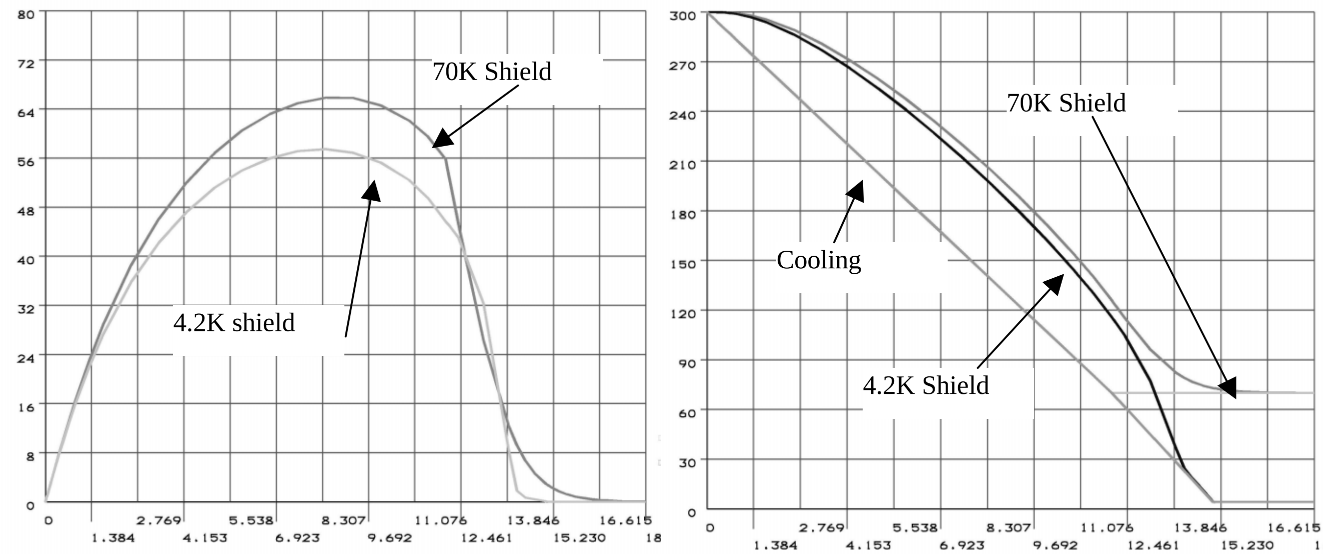

Figure 2. Cooldown simulation of the 4.2 K and 70 K aluminum thermal shields. We used a simultaneous 12 hour linear cooldown (right graph). The maximal thermal gradient on the shields (left graph) is below 70 K, a safe value.

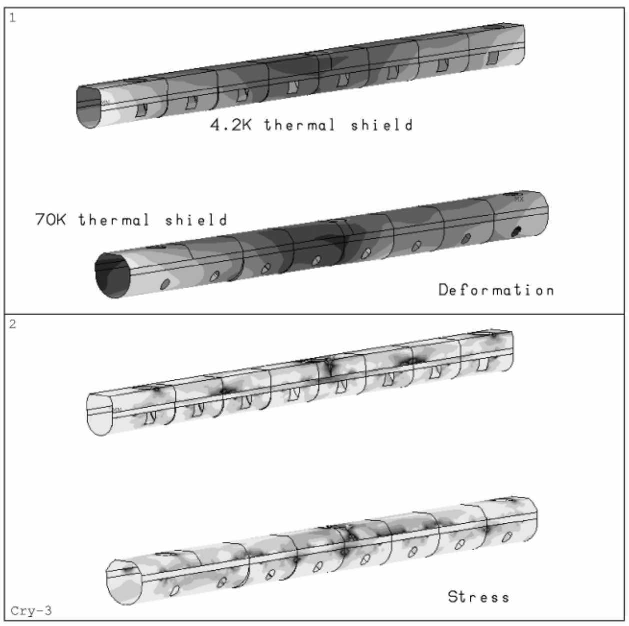

Figure 3. Thermo-mechanical analysis of the shield panels. Applying the computed temperature field the deformations and stress distribution can be easily computed. The stresses (lower plot) are within 30 MPa, while the deformation due to asymmetric cooling is below 10 mm (upper plot).

3 CAVITY SUPPORTS

The experience gained during the assembly of cryomodules #1, #2 and #3 showed evidence that the cavity support system could be improved in terms of maintaining the cavity alignment. Due to the geometry of the system, it was too complicate to keep cavities and quadrupole positions within the alignment requirements. The need to develop a system that could, in principle, be compatible with superstructure or semi-fixed couplers led to the decision to complete redesign the cavity supports. The solution proposed and studied needs to keep the cavity transverse position fixed, while leaving the cavity longitudinal position independent from the HeGRP thermal contraction and extension during the cooldown-warmup cycles. These objectives have been reached with a set of low friction sliding supports. A support, whose section is presented in Fig. 4, consists of a C-shaped stainless steel element that clamps to a titanium pad, which is welded on the cavity helium tank. The connection is achieved by a sequence of rolling needles, runners and reference screws. In each constrained direction (vertical and lateral) a reference screw defines the cold position of the cavity axis, and a spring washer package loaded at about 80 kg_f keeps the pad in contact. The friction between the cavity and the support has been measured and results in about 0.6 kg_f [8].

This low friction value results in a decoupling of the cavity longitudinal position with respect to the supporting HeGRP. In order to be compatible with semi-rigid couplers and superstructures, an Invar rod fixture determines the longitudinal position of the coupler ports. This solution results in a maximum total longitudinal motion of the coupler port, from warm to cold, of less than 3 mm.

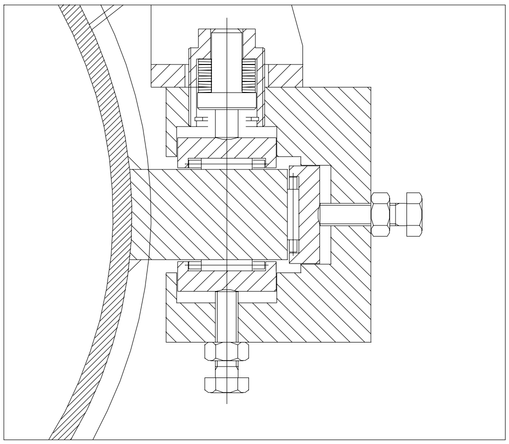

Figure 4. The cavity support system. Four C-Shaped stainless steel elements clamp a titanium pad welded to the helium tank by using rolling needles that reduce drastically the longitudinal friction, leaving cavities independent from the elongation and contraction of the HeGRP. Lateral and vertical positions are defined by reference screws.

4 TOLERANCES AND ALIGNMENT

Analyzing the motion of the active elements during the cooldown of cryomodules #1 and #2, as measured by the installed Wire Position Monitor system [3, 6], we have determined the presence of asymmetric forces in the feed-cap and end-cap sections of the module. These forces probably are generated by the misalignment of the HeGRP of the two consecutive modules, deforming the HeGRP, and moving the active elements out of alignment tolerances. To reduce this effect, two major improvements have been included in the present design.

First, we changed the longitudinal positions of the support posts. The most critical component, from an alignment point of view, is the quadrupole. Therefore, a support post has been placed over the fixture of the quadrupole package. The other two posts have been placed, compatible with the assembly procedures, at positions that reduce the static deformation. To check this new solution, a combination of 1 kN forces in all directions have been applied to the extremes of the HeGRP, and the induced deformations have been computed [Fig. 5]. The displacement in the cavity region is within 0.2 mm in the worse situation, while at the quadrupole it is estimated to be less than 0.1 mm. In order to further simplify the design, the support of the vacuum vessel has been modified. In the new design, the same supports are used during assembling and in the linac operation. The positions have been chosen using the same philosophy as the HeGRP support, in order to minimize the reaction to unknown forces during operation. Due to these changes, all the assembly tools have been redesigned to fit the new geometry.

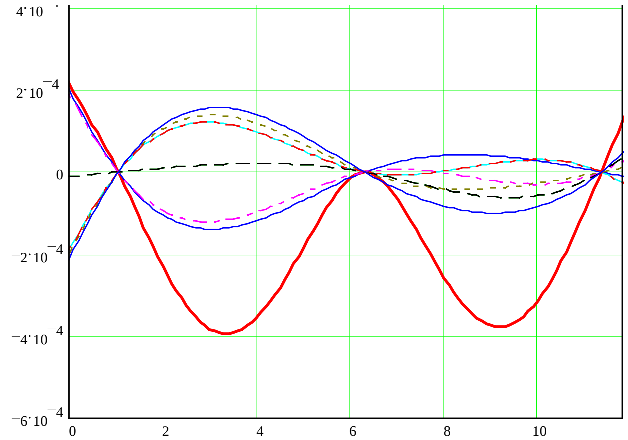

Figure 5. Computed deformation of the HeGRP when stressed by 1 KN asymmetric forces in the end cap and feed-cap positions. The overall deformation is less than 0.2 mm in the cavities region and less than 0.1 mm for the quadrupole package.

One other major improvement follows from the decision to include the bellows that links the HeGRP of two different modules in the fabrication of the HeGRP itself. This has increased the free space in the interconnection of the modules, and has extended to the bellows flange the fabrication tolerances. The fabrication tolerances of the HeGRP are achieved by a 12-m milling machine that references flanges and support element defining the axis of the tube. This operation can now be extended to the bellows flange. As a consequence the bellows is referenced to the cryomodule axis and the connection between two consecutive HeGRP is more precise, and consequently less stressed. The result of this choice in the fabrication philosophy should be a sensible reduction of the external forces during pressurizing and cooldown.

The combination of the new support positions and fabrication process should achieve the cold alignment requirements for the cavities and the quadrupole package needed by the TESLA Collider Project

5 PROTON LINAC MODULE

Within the framework of the Franco-Italian collaboration for an high power proton accelerator (HPPA) to drive a reactor subcritical system (ADS), the experiences accumulated in the design of the TESLA cryomodule have been applied to the cryomodule design approach for the high energy superconducting part of the accelerator, that is foreseen to start at an energy close to 90 MeV (proton beta ~ 0.41).

In the actual linac design, modules are independent cryogenic units. In the first two sections each module houses two cavities, while for the high beta section four cavities per module are foreseen. To make possible the use of the bigger high power RF coupler, derived from the APT design, a different approach has been chosen for the vacuum vessel. The vessel has a large lateral flange that give access to the whole vessel. A pictorial view of the module concept is presented in Fig. 6.

Cavities housed in their helium vessels are assembled and aligned on a referenced frame inside a class < 100 clean room. Once the cavity string is completed, including RF power couplers, and closed with vacuum valves, it is moved on its frame into the vacuum vessel. The alignment is preserved by the use of an identical referenced rail system in the vacuum vessel and in the clean room to reproduce the position of the cavity string supporting frame, i.e. of the cavities themselves.

A single shield at 40 K, based on the well understood "finger welding" technique, has been preferred, given that the dynamic losses are dominant. The cavities are supported by the TESLA like sliding fixtures.

The detail design of this module is now under way within the framework of the Franco-Italian collaboration for ADS. We expect to have the first two cryostat prototypes fabricated in 2001 and to test them with cavities and ancillaries by end 2003 [9].

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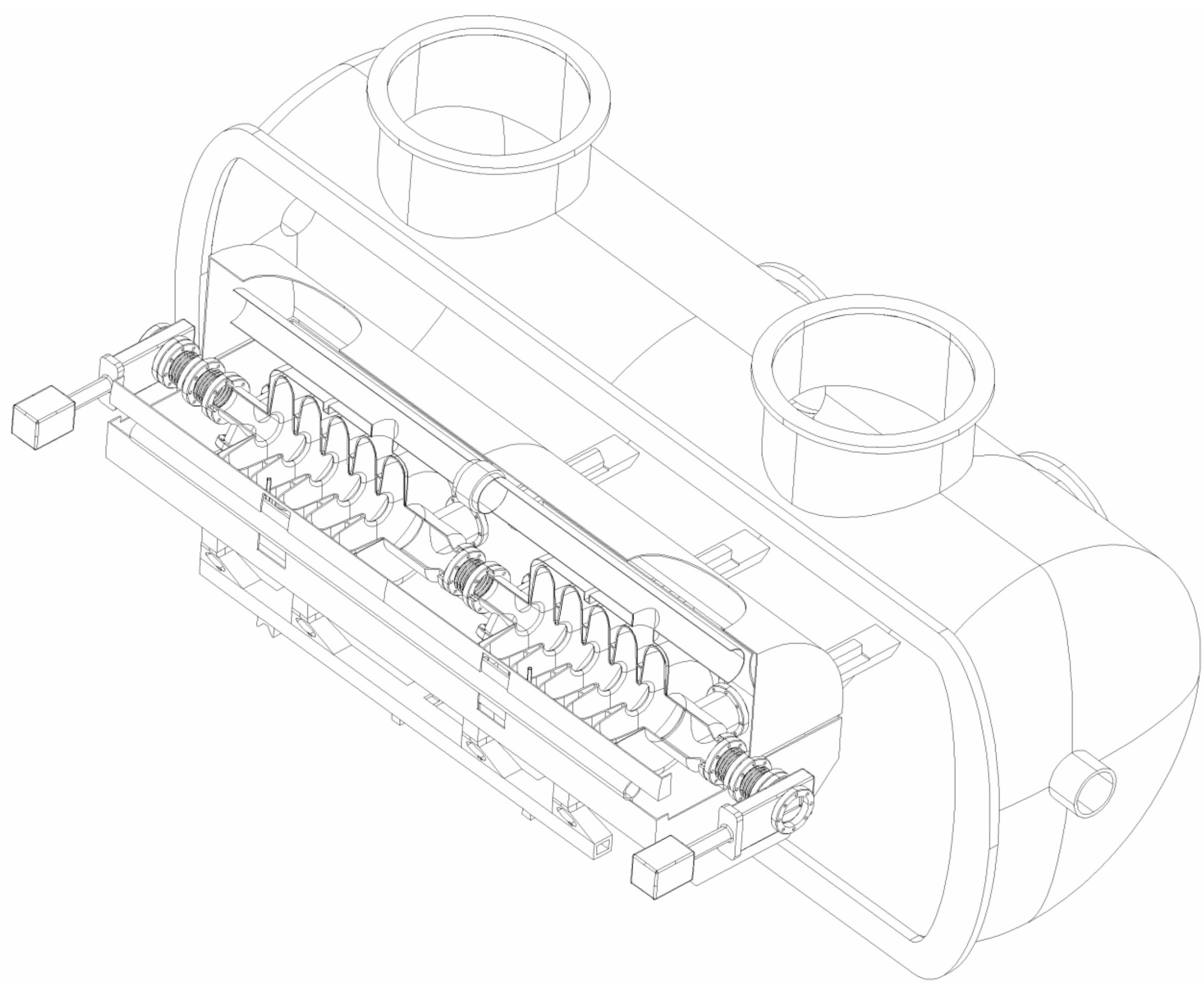

Figure 6. Pictorial view of the cryomodule concept presently under design in the framework of the Franco-Italian collaboration on ADS. This two-cavity module is foreseen for the first two beta sections.